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Specifications, Architecture and Technology for High Resolution ECM

Final Report

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EXECUTIVE SUMMARY

Modern targeting radar technology will continue to evolve to include radars capable of ultra-high resolution in the spatial and Doppler domains. This poses challenges for coherent ECM because high radar resolution can reduce the effectiveness of both obscuration and deceptive techniques.

In order to meet these challenges in the medium and long term, ECM equipment must improve in five main aspects:

1. more precise control of time delays and Doppler values
2. ability to superimpose multiple pulse reconstructions signals which are slightly shifted in range
3. ability to generate closely spaced Doppler components without intermodulations
4. ability to produce short profiles to allow time-sharing within a coherent dwell
5. ability to compute and control compensations for platform motion parallax
6. ability to control end-to-end gain and maintain linearity

Item 1 is facilitated by advances in digital memory speeds and digital synthesis for precise delay and Doppler resolution respectively. The ability to take advantage of this potential resolution may not, however, be present. As an example, one laboratory jammer was not initially able to provide a sufficient number of control bits for its direct digital synthesis (DDS) chip. Two advanced coherent jammers, though sampling at very high rates, were found to limit the resolution at which the delay can be commanded. This was a consequence of having been designed for bandwidth rather than maximum time precision. Thus the inherent potential for ultra-fine resolution in range delay for these jammers cannot be realized without a redesign of control logic for the digital RF memory (DRFM).

Item 2 requires multiple independent delay paths which can then be combined in order to generate false returns which are spaced closer together than the radar pulse width. In principal, this is convenient to do digitally since the data is already in sampled digital form. If, in practice, there is no way to access digital output on the DRFM, then a digital approach cannot be easily achieved. A DRFM-based jammer could be designed from the outset with the ability to play back more than one analog output from the same memory store with arbitrary delays, but this capability is not presently available. Combination by digital computation rather than analog combiners has the advantage of being extremely flexible and reducing the amount of analog hardware needed. This computed approach is likely an economical way of achieving many hundreds of delay taps and is now within reach of current high end digital signal processing hardware.

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Item 3, the ability to generate arbitrary Doppler modulation, is limited both by the means to produce the Doppler signals and the means to achieve the modulation. Doppler signals are typically generated using a limited number of DDS sources, and modulation is typically done using a single in-line mixer which cannot produce closely spaced Doppler signals without introducing intermodulation products.

The first problem could be handled by generating the waveforms digitally using software algorithms (or perhaps a waveform table) rather than hardwired devices. The Doppler signals need only be updated once on every PRI. The second problem could be handled by a novel approach described in section 4.1.1, which uses phase shifting by programmable direct digital synthesizer (DDS) in combination with a programmable attenuator to impose arbitrary Doppler modulation without intermodulation problems. Another approach (also described in section 4.1.1) is to use multiple mixers followed by a power combiner to reduce intermods.

Shortcomings in items 2 and 3 can sometimes be compensated for by strength in item 4, the ability to produce short profiles. If multiple closely spaced range targets or Doppler signals cannot be generated simultaneously, then they can sometimes be generated serially at much lower cost. This tactic, however, reduces the Doppler resolution observed by the radar and requires knowledge of the coherent dwell time used by the radar. This method can reduce the number of separate delay paths and mixers needed, but it is by no means equivalent to a parallel approach.

Item 5, ability to compute and control compensations for motion parallax, is necessary because the range and Doppler that the radar expects for a given false target position will typically change over the radar field of view. A false target generated by a coherent repeater will typically have the range and Doppler characteristics of the jammer, which will often be inappropriate for a false target. High resolution radars are able to resolve differential changes in Doppler and delay due to different relative platform motion across the field of view of the radar. The signal processing for high resolution radars ordinarily must account for these variations, with the result that an un-compensated false target may not be properly focused or may 'walk' across range gates and Doppler bins.

These compensations are certainly achievable, though more research and modelling is needed to generate the formulas needed to calculate them. Typical jammers may not allow the delays and Doppler modulations to be flexibly controlled. If the threat geometry is not known in advance, it may be necessary to calculate the required compensations on-the-fly, so that the techniques controller must be flexible, programmable, and tightly coupled to the ECM control. Typical jammers which require that all parameters and profiles on delay and Doppler be downloaded in advance may not be flexible enough to operationally meet threats such as airborne SAR.

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Item 6 (controlled gain and good linearity) is important for deceptive applications so that apparent RCS is independent of radar range and mode, and also to avoid unwanted Doppler intermodulation products.

For jammers with limited dynamic range DRFMs, the power level at regeneration can be controlled to produce the effect of an approximately fixed gain which translates to a fixed RCS. Current approaches do not use a measurement of the input power level to control the output power. Instead, the output amplifier is saturated, which can result in unrealistically bright false targets as well as unwanted harmonics and intermodulations.

Jammers which use DRFMs with a large number of bits, and which hence inherently possess wide dynamic range and good linearity can be contemplated. Advances in civilian technology for A/D and D/A components will make high dynamic range DRFMs feasible at ever higher bandwidths.

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RECOMMENDATIONS

The following recommendations are offered in order to increase Canadian capability and understanding of ECM for high resolution radars:

1. Modify available laboratory jammer to increase available Doppler resolution *Note: already implemented*

2. Modify available laboratory jammer to allow very short range and Doppler profiles. *Note: already implemented*

3. Implement linear (low-intermodulation / low harmonic) Doppler modulation techniques such as DDS phase shifting with programmable attenuation.

4. Identify changes required to the current DRFM design to allow more precise control over regeneration delay, variable sampling rates, digital I/O, and flexible addressing.

5. Investigate modelling of encounter geometry to allow compensation of differential motion parallax which will affect both Doppler and range for high resolution radar ECM.

6. Investigate digital tapped delay architectures (or high speed digital output) and digital storage technology which could be used in future DRFM design or specification efforts (e.g. high speed FIFO memory).

7. Review digital signal processing technology and algorithms for application to computed HRECM.

8. Improve linearity of the end-to-end system to avoid intermods, and investigate feasibility of producing a constant end-to-end gain under programmable control.

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1.0 Introduction

This working document describes our understanding of the technical requirements, architectures, and key technology improvements for ECM against high resolution radars, with emphasis on airborne and spaceborne naval targeting radars. This work is driven by advances in high resolution radar technology which will not be adequately countered by ECM capability if current jammer technology is not extended. We start from the assumption that coherent storage and reconstruction of the pulse will be required. We further consider the use of digital sampling and storage to be a baseline requirement for an HRECM-capable jammer.

This research is not tied to a specific piece of hardware at present, but is instead an effort to look ahead to types of systems which might reach the laboratory proof-of-concept stage in 5 years and be fielded 10-15 years from now. At the same time, we expect that some of the requirements identified here can be met by modifying existing laboratory equipment, thus realizing short term benefits.

The target specifications presented in section 2 are for an ideal system that should be able to counter the highest performance radars of today. It is likely that a lesser level of performance would be adequate for many applications.

The architecture discussion of section 3 starts with a general model of ECM generation based upon combination of multiple delayed and modulated reconstructions of the captured pulse. The delay, modulation and combination may be achieved by analog means, by digital means, or by a combination of both types of technology. Digital implementation can include digital computation using arithmetic within a digital signal processing computer. It will be argued that ECM with relatively few simultaneous range targets and Doppler can be most easily produced with analog means, while ECM with a large number of simultaneous and independent range and Doppler targets are practical only with a computed approach. A compromise HRECM architecture which supports both approaches is presented at the end of section 3.

Section 4 discusses key technology improvements which are believed to be important for the HRECM application. These are divided into digital and analog technology improvements.

Much of the work presented here is based upon experience with spaceborne SAR ECM for both obscuration and deception. The requirements specifications for other types of threats are not yet supported by field experience. These will no doubt be refined as we gain experience with other types of threats.

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1.1 Document Scope

This document discusses target technical specifications, architectures alternatives, and key areas for technology improvement. No attempt is made to offer a definitive design or perform detailed design trade-offs for an HRECM system.

Target technical specifications are discussed in section 2.0, and high level architecture alternatives in section 3.0. Section 4.0 is devoted to identification of needed technology improvements. Emphasis throughout is on naval counter-targeting ECM against airborne or spaceborne radars, but much of the report should also be applicable to other environments and types of high resolution radar.

1.2 What Do We Mean by High Resolution?

We use the term *high resolution radar* to denote a radar with high resolution in space, in Doppler, or both. Examples include synthetic aperture radars (including inverse SARs), high range resolution radars, range/Doppler profiling radars, and long-dwell pulse-Doppler radars intended to achieve very fine frequency resolution.

High resolution is a relative term. For our purposes we mean resolutions in space of tens of metres or better, and potentially down to several centimetres in the extreme. High Doppler resolution will mean resolution of a few Hertz, and potentially as good as a fraction of a Hertz in the extreme.

1.3 Problems Presented by High Resolution Radars

High resolution radars present special problems for electronic countermeasures (ECM). These problems generally fall into two categories:

1. The high resolution radar system is able to defeat many ECM obscuration techniques by virtue of fine discrimination in range and Doppler.

2. The high resolution of the radar demands more sophistication in deceptive techniques because false targets must be represented more accurately and in greater detail.

Included in category one is the ability of some pulse compression radars to reject many kinds of ECM. An unmatched ECM signal is spread out over the uncompressed pulse width, whereas a real return is properly resolved into a small number of range cells. The consequence is that ECM power must be spread thinly over a large number of resolution cells and can fail to obscure.

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Another example is the ability of Doppler radars to counter many kinds of non-coherent ECM. The ECM power is spread over too many (or the wrong) Doppler bins, and fails to obscure the true signals.

When the radar has high resolution in two dimensions (e.g. a synthetic aperture radar or range Doppler profiler), the space across which ECM must be projected is quite large. Where power is limited, ECM power must be made to fall within the spatial and/or Doppler resolution cells where it will do the most good.

Category two incudes the ability of SARs or ISARs to identify ship formations or sub-features of individual ships, either spatially or as a range-Doppler profile. A point target with a single pure Doppler will not be mistaken for a real ship, which has spatial extent and Doppler features. Furthermore, formations of ships in overly regular patterns will likely cue the operator that something is wrong.

Another example from category 2 is the ability of some types of long-dwell pulse Doppler radars to identify Doppler modulation signatures of real targets (e.g. jet engine modulation signatures). A deceptive target may have to realistically reproduce such detailed signatures.

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2.0 Target Specifications

This section deals with the target technical specifications for a hypothetical ideal system designed for a very broad spectrum of high resolution ECM (HRECM). We begin by identifying the classes of *radar threats* that should be considered and their general characteristics. We next identify the *jammer* characteristics of importance, and the specifications required to handle the most demanding threats.

2.1 Types of High Resolution Threat

The types of high resolution threat considered are as follows:

- Strip mapping synthetic aperture radar (SAR)
- Spotlight synthetic aperture radar (SAR)
- Inverse synthetic aperture radar (ISAR)
- High Doppler resolution radar
- High range resolution radar
- Low Probability of Intercept (LPI) and Pulse Coded radars

Both airborne and spaceborne radars are of interest.

2.1.1 Strip Mapping SAR

A strip mapping SAR uses a more-or-less sidelooking antenna on a moving platform. Along-track resolution is achieved using the synthetic aperture principle which relies upon Doppler processing. Range resolution is usually achieved using pulse compression waveforms, though unmodulated short pulse systems are also possible (e.g. the Russian ALMAZ spaceborne SAR).

Strip mapping SARs usually achieve resolution on the order of 1-30 m in each direction.

The dwell time of a typical strip mapping SAR is on the order of a second, which implies Doppler resolution on the order of 1 Hz. The Doppler bandwidth is a few hundred Hz for airborne systems, and on the order of 1500 Hz for spaceborne systems.

Strip mapping SARs produce long strips of imagery along track, and the width of the image along the ground in the range direction is typically 40-500 km wide.

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2.1.2 Spotlight SAR

A spotlight SAR observes a small ground patch over a relatively large angle during flight to achieve extremely high cross-range (azimuth) resolution. Spotlight SAR thus requires an antenna which has azimuth steering capability (electronic or mechanical), and tracks the area of interest as the radar platform flies. The spotlight SAR achieves finer azimuth resolution than strip mapping SAR, which is typically paired with finer range resolution.

These systems can achieve resolution well below 1 m in each direction.

The dwell time of a typical spotlight SAR is on the order of ten seconds. The PRF is on the order of thousands of Hz.

Spotlight SARs can produce short stretches of imagery along track, with a coverage on the order of 10 km on a side.

2.1.3 Inverse SAR

An inverse SAR (ISAR) relies upon the motion of the subject (e.g. pitching and rolling ship, aircraft in flight) for its resolving power. The subject motion generates Doppler modulations which are correlated to individual component scatterers. The need to lock the antenna onto the moving subject, combined with the fact of ownship motion for airborne and spaceborne platforms, usually requires antenna steering capability.

These systems usually achieve resolution below 1 m in each direction, or a fraction of a Hertz if using range-Doppler profiling.

The processed dwell time depends on the speed of the target angular motion and can vary from a faction of a second to several seconds. The PRF can also vary widely but may be similar to that for spotlight SAR.

2.1.4 High Doppler Resolution Radar

A high Doppler resolution radar is distinguished by a relatively long dwell time, on the order of a second or more. This corresponds to resolution better than 1 Hz. Thus, spotlight SAR (and sometimes ISAR) are forms of high Doppler resolution radar and have been discussed above.

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Any Doppler radar with a long coherently-processed dwell mode is a high Doppler resolution radar (e.g. CW air ISAR radar or some tracking radars).

2.1.5 High Range Resolution Radar

High range resolution radars may use short real pulses or long coded pulses with high compression ratios and no Doppler measurement capability. Other systems will use stepped frequency on a pulse-by-pulse basis. Pulse length could range widely from a few tens of nanoseconds to hundreds of microseconds or even longer.

Range resolutions can be on the order of a few centimetres which corresponds to delays on the order of a nanosecond. If the pulse coding is a chirp, range features can be produced by frequency modulation. The precision required for this depends upon the chirp rate, but may typically be in the kilohertz range.

If range features must be produced by time delays, delays in the nanosecond range are needed. The pulse repetition frequency can vary widely and may be staggered.

2.1.6 LPI and Long-Pulse Coded Radar

Low Probability of Intercept (LPI) and other pulse coded radars with long pulse widths can achieve relatively fine range resolution and long range with relatively long pulse widths and low powers. For LPI the goal is to get the power level below the noise floor to reduce detectibility by EW equipment. High Range Resolution radars may use pulse coding to get fine resolution at long range within reasonable power limits.

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2.2 Discussion of Jammer Characteristics and Requirements

This section describes jammer characteristics of interest for HRECM. Where possible, we discuss required specifications for these characteristics in order to counter high resolution radar threats.

TABLE 1: Summary of Target Specifications

SUBSYSTEM	ATTRIBUTE	SPECIFICATION	COMMENT
ANTENNA SYSTEM	Number of Apertures	2 (Separate Tx / Rx)	Non-specific to high resolution radar, but desirable to allow simultaneous Tx/Rx
	Gain	10-20 dB	Dependent upon threats. Many high resolution radars may have low power, and therefore high Rx gain is desirable
	Mount	Steerable 360° az, 90° el	High elevation coverage requirement is unique to spaceborne threats.
RF SYSTEM	Bandwidth	500 MHz	High bandwidth needed to counter short-pulse or coded pulses with large bandwidths.
	Triggering	Triggered or Continuous	Continuous operation (no triggering) could be useful for LPI waveforms which may not be detected by a triggering circuit.
	Noise Figure	Approx 3 dB	High noise figure can produce an elevated noise floor which could spoil deceptive techniques.
	Tx/Rx Isolation	At least 90 dB	Needed for simultaneous Tx/Rx. Not specific to HRECM, but challenging for spaceborne geometries.
	Tx Power	250 W to .01 W, gain accurate to 3 dB	Very large dynamic range needed if jammer is to serve for both deception and obscuration. Controlled gain and low power are specific to deceptive applications.
	Intermodulations and Harmonics	Better than -20 dBc	Imaging or profiling systems can discern intermodulations which could cue the operator

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RANGE DELAY	Maximum storage length	1 millisecond	Many high resolution radars use pulse compression. This allows use of very long pulses with improved energy on target.
	Number of range targets	10 or more	HR radars can resolve individual components of a target, so deceptive ECM must build up a constellation of scatterers.
	Minimum target spacing	1 nanosecond	Must support closely spaced scatterers.
	Delay repeatability	1 nanosecond	Must maintain pulse-to-pulse stability to exploit Doppler processing gain
	Delay resolution	1 nanosecond	Must be able to control target trajectory to model expected range cell walk expected by radar processor
	Range profile length	0.01 to 100 seconds	Short profiles needed if time sharing is used over a short radar illumination time. Long profiles may be needed to avoid obvious repetition.
FREQ MODULATION	Maximum Doppler shift	300 kHz	Doppler need only match highest expected PRF
	Number of components	greater than 10	Profilers or SARs will resolve in Doppler or azimuth dimension, and realistic false targets must have realistic structure.
	Doppler accuracy	0.1 Hz	Some radars may dwell as long as 10 seconds, implying this Doppler resolution.
	Doppler resolution	0.1 Hz	Changes in Doppler must move without discernable 'jumps'.
	Maximum chirp shift	250 MHz	Useable chirp shift could be as much as half the highest expected pulse bandwidth.
	Doppler profile length	0.01 to 100 seconds	Short profiles needed if time sharing is used. Long profiles may be needed to avoid obvious repetition.
	Relationship to range targets	> 6 independent Dopplers	Necessary to realistically model targets in Doppler

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AMPLITUDE	Dynamic range	30 dB	Needed to allow realistic RCS independent of range or mode
	Accuracy	TBD	Needed to meet operator expectations of RCS level
	Resolution	TBD	Must avoid obvious steps in relative brightness.
	Profile length	0.01 to 100 second	Short profiles needed if time sharing is used. Long profiles may be needed to avoid obvious repetition.
	Relationship to targets and Doppler	Independent of target range and Doppler	Necessary to realistically model target amplitude differences.

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2.2.1 RF Front End Characteristics

In this section the jammer RF front end is considered specifically from the point of view of HRECM, and special considerations are highlighted.

2.2.1.1 Antenna System

Considerations for the HRECM antenna system are similar to those for other types of ECM systems. The major considerations are gain vs beamwidth, acquisition and tracking, and number of antennas.

High gain is desirable, but leads to narrower beamwidth which complicates acquisition. Where spaceborne or LPI radars are considered, high receive antenna gain may be desirable to maximize the received signal power. If the orbital geometry is known, acquisition can be simplified, and tracking may be unnecessary. In this case narrower beamwidth can be tolerated if pointing is precise.

In general, a tracking ability would be desirable given that some types of high resolution radar (e.g. airborne) have flexible geometry. It should be noted that spaceborne radars will have higher elevation acquisition angles than encountered in airborne cases, necessitating a full zero to ninety degree elevation capability.

Where transmit and receive must be simultaneous, two antennas may be needed to achieve sufficient isolation, especially in spaceborne cases. Simultaneous Tx/Rx may be needed if the false target is to be placed directly on top of the jammer site, or where a long pulse radar is being countered and a false target is to be placed very close to the jammer position. Another case is when received powers are so low that triggering cannot be reliably done, and the reconstruction is done on a continuous delay basis (see section 2.2.1.3).

2.2.1.2 RF Bandwidth

The RF bandwidth required for a high resolution radar can be very high if range resolution is achieved using a wide bandwidth pulse. Bandwidths of as much as 500 MHz may be required for extremely large bandwidth signals such as chirp waveforms.

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2.2.1.3 Triggering

Triggering is a problem for LPI radars and possibly for long range radars with very long coded pulses. By design or necessity, the incoming pulse signal power may be near or below the noise floor, and thus the system will not be able to trigger a storage device reliably.

Systems which continuously receive and transmit a delayed signal could be used in such cases. This would dictate two antennas as noted above, and also sufficient Tx/Rx isolation (see section 2.2.1.5).

A continuous regeneration jammer system would require constant end-to-end gain and low noise figure since the power level of the incoming signal is unknown and not measurable beneath the noise floor. Since noise (as well as any LPI signal) would be continuously amplified and transmitted, this kind of jammer is aimed at deceptive ECM where power levels may be low enough that the elevated noise floor might go unnoticed.

2.2.1.4 Receiver Noise Figure

Low receiver noise figure is desirable and is important if the receive power is very low, as is typically the case for spaceborne threats. Ideally the noise figure should be similar to that of the threat radar to avoid introducing a noticeable increase in the noise floor when attempting deception.

2.2.1.5 Tx/Rx Isolation

Transmit/receive isolation is especially important if the radar is to be simultaneously transmitting and receiving. From our experience with spaceborne ECM, isolation on the order of 120 dB is desirable but not normally achievable. Lesser isolation may still be very useful especially for airborne applications.

2.2.1.6 Transmit Power Levels

Transmit power levels vary widely depending upon the type of radar and the engagement geometry.

An ability to transmit high power is always desirable, especially for obscuration. However, for many types of pulse compression, Doppler and SAR radars, very low power levels are desirable. This is the case when attempting to produce a realistic false target.

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The ability to transmit well-controlled low power levels which are a fixed gain relative to the received power is valuable for deceptive ECM. The controlled gain factor can provide an apparent constant radar cross section even at varying ranges and geometries, and even when the threat radar characteristics are largely unknown.

One typical DRFM based jammer compresses an input dynamic range of 60 dB to 6 dB at the DRFM input to match the dynamic range of the DRFM A/D converter. To achieve constant gain in this case would require measuring the incoming pulse strength and adjusting transmit power appropriately. Alternate jammer architectures could be explored which use a large number of A/D bits to preserve good linearity over a wide dynamic without compression.

Transmit power levels well below one Watt may be needed for some deceptive techniques, especially for the spaceborne case where power levels are very low and a large amount of signal processing gain may be used.

Low transmit power capability may dictate the use of more than one type of power amplifier (See section 4.1.2). Highly linear low noise solid state amplifiers should be used at low power, while a TWT can be used at higher powers for obscuration.

2.2.1.7 Intermodulations/Linearity

Deceptive HRECM techniques often need to have good control over the imposed Doppler, which will in general have several simultaneous components. Intermodulations or harmonics should be kept to level where they will be near the noise floor when a realistic target is to be created. Typically the intermodulation products and harmonics should be held below -20 dBc.

Many jammers are run near saturation at several points in the system. Intermodulations and harmonics are the result. Normally harmonics fall outside bandpass filters, but intermodulations are normally inside the pass band. Whereas intermodulations are not present when a single Doppler is imposed, multiple Dopplers needed for realistic HRECM can lead to serious unwanted intermods if the system is not linear at all mixers and amplifiers.

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HRECM therefore puts a much higher value on system linearity than typical air applications. See sections 4.1.1 and 4.1.3 for further discussion of relevant technology.

2.2.2 Range ECM Characteristics

Range ECM is normally controlled via time delays in waveform reconstruction. While some types of radar which use stretch processing resolve range using frequency, such cases can then be regarded as Doppler ECM and are deferred to section 2.2.3.

2.2.2.1 Maximum Stored Pulse Length

Maximum stored pulse length in time should be sufficient to handle the longest pulse width likely to be encountered. A millisecond should be sufficient storage for most threats.

It would be desirable to allow variable sampling rates to allow a trade-off to be made between pulse length and pulse bandwidth. The length of pulse that can be stored can be extended if the pulse bandwidth is less than the maximum system capacity (see section 4.2.2).

If continuous regeneration (i.e. no triggering) with fixed delay is used to counter an LPI threat, the maximum delay is the same as the maximum storage length.

2.2.2.2 Number and Spacing of Range Targets

The requirements for number and spacing of range targets can be very demanding for a deceptive technique countering a high resolution radar system.

If a realistic false target is to built from point targets, tens or hundreds of closely spaced point targets in range may be required. Fortunately it is often possible to simulate the effect of many point targets by moving one or a small number of point targets in range over the radar observation interval. Nevertheless, there may still a need for substantial number of distinct range targets if the radar covers a large area (e.g. a strip-mapping SAR), probably on the order of 10.

Where the pulse length is long (yet resolution in range is high), it will be

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necessary to superimpose the reconstructed pulses to form multiple closely-spaced targets, either because the PRI is not sufficient to fit a large number of targets, or because targets must be placed closer together than one pulse width.

Superposition of reconstructed pulse implies that there is a need for some form of delay and add capability. The delay should ideally be programmable and could be either analog or digital. The superposition of pulse reconstructions could be achieved by analog combining, digital addition, or a combination of both. Section 3.3, 4.2.3 and 4.2.4 discuss architecture and technology aspects of range delay in more detail.

2.2.2.3 Range Shift Resolution and Range Profiles

The repeatability of the reconstruction delay should ideally be equal to the time equivalent of the range resolution of the radar. For high resolution radars, the delay may have to be controlled down to the nanosecond.

The ability to change range over time (i.e. RGPO) must also be controlled within the time equivalent of the range resolution of the radar so that a pull in range will be realistically smooth.

2.2.3 Doppler ECM Characteristics

Doppler ECM is relatively low frequency modulation intended to mimic the Doppler caused by relative radial motion between the radar and targets within the antenna beam. Where the resolution is high, targets which follow different paths may be resolved. A HRECM jammer which can handle Doppler threats must be able to generate a large number of Doppler components, each of which may be of different amplitudes.

Larger frequency shifts may be used in order to achieve apparent range displacement of a chirp waveform. These larger frequency shifts are much greater in magnitude that those which would be caused by Doppler effects at reasonable speeds and wavelength. Nevertheless, we discuss the generation of these larger ECM frequency shifts in this section on Doppler ECM because the same techniques can be used to generate both types of frequency shift.

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2.2.3.1 Maximum Doppler Shift

For Doppler radars, the maximum Doppler shift required will be equal to the PRF. This means that hundreds of kilohertz are sufficient where Doppler frequency shifts alone are concerned. The precision required depends on the Doppler resolution of the radar, and this topic is discussed in section 2.2.3.3.

When the pulse waveform is a chirp, however, it is sometimes desirable to impose a frequency shift of several megahertz (or some significant percentage of the chirp bandwidth) in order to shift the apparent arrival time of a pulse after pulse compression. This technique is called "chirp shift".

This kind of frequency shift is not intended to be interpreted as a Doppler shift by the radar, and would be a significant fraction (e.g. 5-50%) of the pulse bandwidth. For very high bandwidth chirps, this shift may be as much as hundreds of Megahertz.

Where a Doppler radar is to be countered using chirp shift, a large shift must be applied. Small differences of a few Hz will have little effect on the chirp shift range displacement achieved, but may have a significant effect on the *Doppler* observed. In such a case, the Doppler frequency observed will be the large frequency shift *modulo* the radar PRF. This is the well-known aliasing effect.

A full featured HRECM jammer, therefore, should be able to produce large frequency shifts, and the precise frequency may have to be fine tuned within a range equal to the highest PRF likely to be encountered (see section 2.2.3.3).

2.2.3.2 Number and Spacing of Doppler Components

If a radar has very high Doppler resolution, it may be necessary to provide a very large number of Doppler components in order to produce a realistic deceptive target. This may be so because of complex motion of the target and its parts (e.g. helicopter), the presence of several scatterers at the same range gate position moving at different velocities (e.g. ISAR), or due to motion parallax caused by platform motion (e.g. SAR). If a realistic profile in Doppler is needed, tens or even thousands of components might be needed. In general, each of these components may have different magnitudes.

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As for the range case, it may be possible to move a single Doppler component over a radar dwell time and simulate the effect of many Doppler components. The faster the pull, however, the poorer the Doppler resolution. This shows up as a loss of focus for SARs, and as broadened spectral peaks for pulse Doppler radars and profilers. Also, this approach may be vulnerable to ECCM.

It is desirable to provide at least tens of spectral components so that realistic Doppler or azimuth profiles can be constructed simultaneously. Ideally, an arbitrary Doppler waveform is desirable, and can be achieved using technology identified in section 4.1.1.

2.2.3.3 Doppler Shift Resolution and Profiles

If a radar is able to resolve small Doppler differences, the resolution with which spectral components may be placed must equal this resolution in order to allow deceptive ECM to have full control over the Doppler profile.

The ability to change Doppler over time (e.g. VGPO) must also be controlled to a tolerance equalling the Doppler resolution of the radar. Thus a pull in Doppler will be realistically smooth.

The theoretical Doppler resolution for standard spectral analysis is the reciprocal of the dwell time. Therefore a spotlight SAR may require control over Doppler that is a small fraction of a Hz. This is within the capability of many high precision direct digital synthesis devices.

2.2.3.4 Independence of Doppler and Range

Real targets are able to have range and Doppler characteristics which are independent of other targets, even if those targets are closely spaced. This can be difficult to reproduce with a jammer because often the Doppler modulation is applied to the entire transmission, rather than just individual pulse reconstructions. Where it is desired to place targets close together in range with distinct Dopplers, the problem is even more difficult since the pulse reconstructions may have to be superimposed. The solution is to apply separate Doppler modulations to the different pulse reconstructions before they are added together.

Ideally it would be useful to have a very large number of range targets, each which has a Doppler that can be independent of every other target. This would require separate Doppler modulation of each target and then

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combination of the pulse reconstructions.

Separate analog paths with a distinct mixers can be used for each target, but this can be expensive. Digital computation can delay, modulate and add sampled data to produce an arbitrary number of independent targets, but this requires a great deal of processing power or a large amount of time. This approach is discussed further in section 3.3.

2.2.4 Amplitude ECM Characteristics

Amplitude ECM is used to control the brightness of individual scatterers to allow for realistic profiling, but also to ensure that the overall apparent RCS of a deceptive false target is within a reasonable range and therefore is believable.

Amplitude control for profiling for HRECM may not be needed for applications such as SAR or ISAR where the amplitude can be controlled via Doppler or range profiles which affect the amplitude seen at the output of the processor.

In general amplitude control could be interpreted to apply to not only range targets, but also to individual Doppler components. This would simulate the effect of various sub-targets which fall within the same range gate, but which are of different sizes and moving at different Dopplers.

2.2.4.1 Dynamic Range of Amplitude Control

Large dynamic range is needed in an HRECM jammer both to meet a wide range of threats and to allow a wide variation in threat range and gain. A constant power false target does not follow the expected $1/R^4$ power law with range, and will not appear with a realistic brightness at all ranges. Brightness can be properly controlled at any range with a constant end-to-end gain over a wide dynamic range. A fixed end-to-end gain ensures constant apparent RCS for the false target, and avoids unwanted additional false targets observed through sidelobes which could cue the operator to deceptive ECM.

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2.2.4.2 Amplitude Control Resolution and Profiles

The resolution to which false target strength can be controlled should be fine enough that the operator cannot detect that there are discrete steps in signal strength. This is a difficult requirement to specify because it will depend on human factors, and may also depend on the brightness resolution of the radar display. Some digital strip mapping SARs provide 16 bit image data, which in theory supports very precise amplitude measurement. Video displays will have much smaller dynamic range.

Ability to control ECM amplitude may also be useful to counter some forms of ECCM which detect the unnaturally stable output of simple repeater jammers.

2.2.4.3 Independence of Amplitude Control

Ideally, each target with a distinct range and Doppler should be capable of being independently controlled in amplitude. Applying an amplitude control prior to Doppler modulation will allow each range target to have a distinct amplitude. By allowing Doppler modulation to include Doppler components of varying magnitude, amplitude can be made distinct for different Doppler targets at the same range.

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3.0 Jammer Architecture

The overall jammer architecture defines the characteristics of the ECM that can be achieved using the particular structure. A very general structure will be extremely capable and flexible, but will probably be prohibitively expensive to implement. The technology used has a direct bearing on cost measured in dollars, reliability, size and weight and will dictate what architectures are practical.

3.1 A Generic Jammer Architecture

A generic HRECM jammer architecture can be defined schematically as shown in Figure 1. The diagram is not intended to imply any particular technology selection, but instead deals with the structure of the jammer itself. In particular, any of the components might be implemented in either analog or digital technology. A large number of possible jammer architectures could be defined as a subset of the generic architecture by removing some of the components in the name of economy.

In a typical modern jammer, the pulse storage and regeneration is done using a DRFM with analog input and analog output. Such a jammer might use only a single Doppler modulator after the pulse storage and reconstruction stage. The Doppler modulator might be accomplished using several analog signal sources combined to drive a single mixer. This typical jammer is clearly a drastic subset of the generic architecture and has the following limitations:

1. Multiple false targets can only be produced by successive regeneration of the pulse, and therefore false targets may be spaced no closer than the regenerated pulse width.

2. All false targets must have exactly the same Doppler modulation.

The generic architecture of Figure 1 includes up to M parallel *delay paths*. Each of the delay paths could contain a *tapped delay line* and *arbitrary independent Doppler modulators* for each tap. These groups of components are shown inside the dashed boxes of Figure 1.

The delay boxes are assumed to be independently programmable on each PRI. The Doppler modulators are shown as an arbitrary waveform generator (AWG) driving a multiplication box, which is intended to represent a totally flexible modulation.

Near the bottom of each delay path is a combiner to collect all of the delayed and

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possibly independently modulated pulse replicas into a single signal. A common Doppler modulator is introduced at this point to allow the possibility of applying the same Doppler to all of the taps within that delay path. This allows the possibility of removing some or all of the independent tap modulators in favour of a common modulator, while leaving the possibility of multiple delay paths which might have Doppler independence between them.

The use of potentially several delay paths requires a Master combiner to produce a single output. Many jammer architectures would use a single delay path, and the Master combiner would be dropped in these cases.

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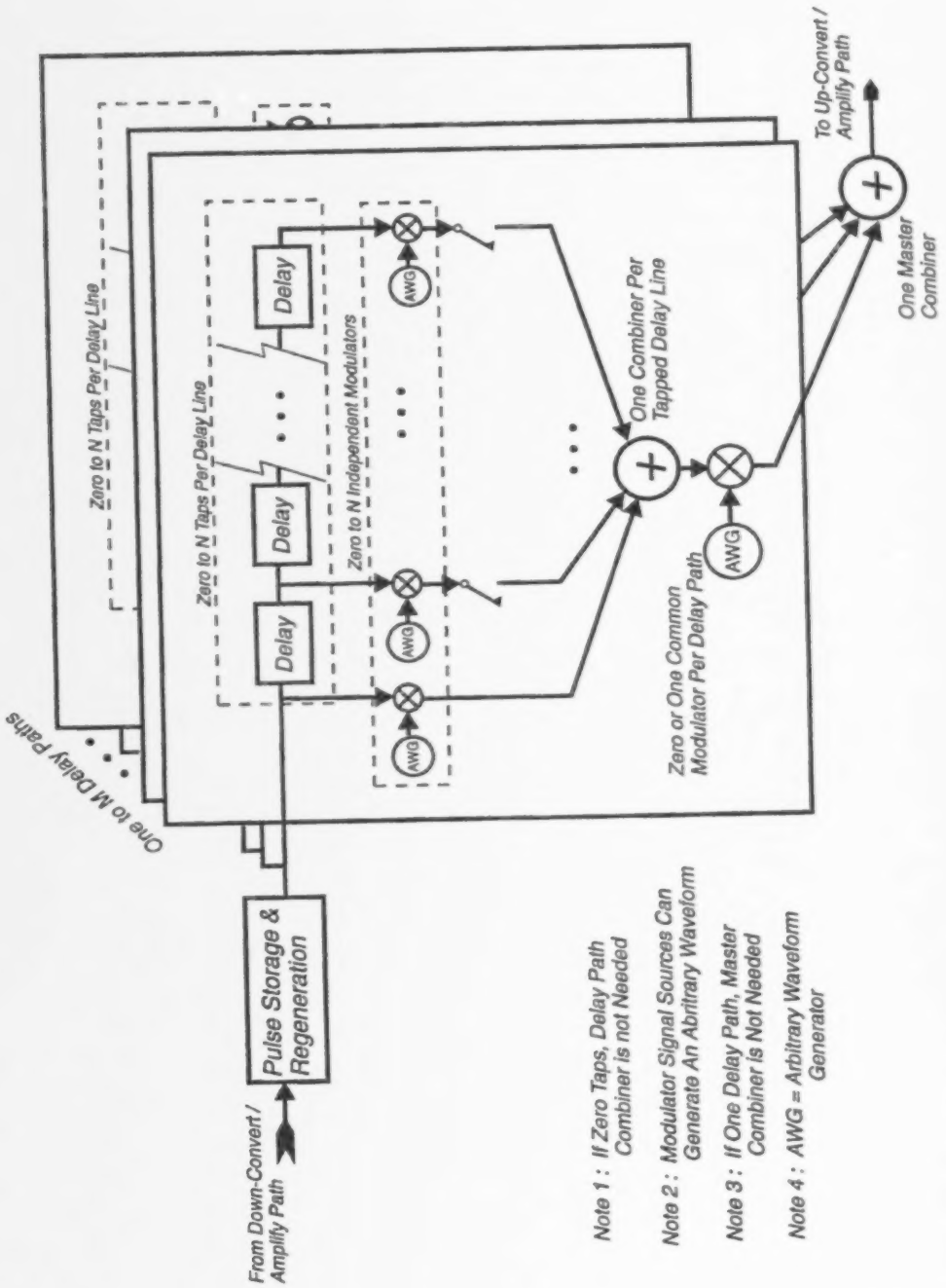
From Down-Convert / Amplify Path
Pulse Storage & Regeneration
One to M Delay Paths
Zero to N Taps Per Delay Line
Zero to N Taps Per Delay Line
Delay
Delay
Delay
Zero to N Independent Modulators
AWG
AWG
AWG
One Combiner Per Tapped Delay Line
Zero or One Common Modulator Per Delay Path
AWG
One Master Combiner
To Up-Convert / Amplify Path
Note 1 : If Zero Taps, Delay Path Combiner is not Needed
Note 2 : Modulator Signal Sources Can Generate An Abritrary Waveform
Note 3 : If One Delay Path, Master Combiner is Not Needed
Note 4 : AWG = Arbitrary Waveform Generator

Figure 1: Generic HRECM Jammer Architecture

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3.2 Digital vs Analog Implementations

Either digital or analog technology may be used for the four basic building blocks of Figure 1:

STORAGE
DELAY TAPS
MODULATION
COMBINATION

Letters can be assigned to each of the four basic elements to describe different classes of jammer as follows:

DDDD	Fully digital system. Requires very fast digital arithmetic to do the combination of the various delayed and modulated signals.
DNAA	First generation DRFM-based jammers with no tapped delay lines, analogue Doppler modulation and analogue combination of the Doppler signals.
DDAA	DRFM-based jammer with programmable digital delay taps, analog modulation, and analog combination.

By definition, all DRFM-based jammers will have digital storage, which indicates a DXXX designation. Older jammers based on frequency memory loops might be described as AAAA class jammers.

3.3 Computed versus Hardwired Approaches

Although digital hardware can be used simply to replace analog devices in the structure shown in Figure 1, a major benefit of digital technology is the potential for replacing fixed signal paths with software algorithms. This has the benefit of improved flexibility and effective use of hardware, but imposes a heavy computational burden.

The major compromise required for the computed approach is that all the computation must be completed within one PRI. If the waveform of the radar is expected to change each PRI, then the computation (and any memory transfers) must be completed within the time offset of the false target. Hardwired approaches, by contrast, can operate almost instantaneously.

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Figure 2 shows a qualitative graph of cost versus complexity for both hardwired and computed approaches.[1] For very simple ECM techniques with a small number of targets, the hardwired approach is simpler than the computed approach and operates almost instantaneously. As the complexity of the ECM technique increases, however, the cost of the hardwired approach will rise sharply and overtake the cost of a computed approach. Once the expense of providing a high speed DSP engine has been incurred, arbitrarily complex techniques can be generated, limited only by the compute time available.

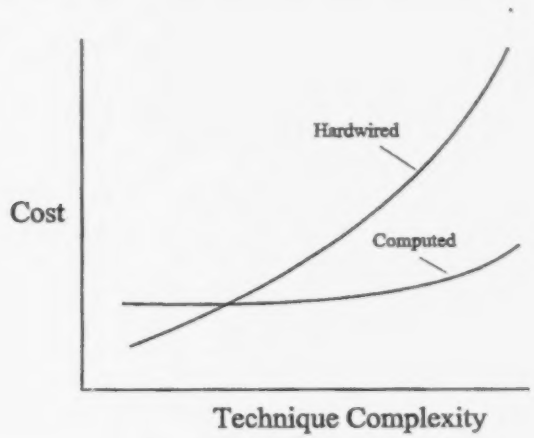

Figure 2: Qualitative Cost versus Technique Complexity

Figure 3 represents a fully computed, fully digital DDDD class jammer. A powerful digital signal processing (DSP) engine has access to the DRFM memory, allowing the DSP computer(s) to read the captured pulse from memory, perform arbitrary computations on the waveform, and then place the result back into DRFM memory for playback of the desired portion of memory. Note that the DRFM can be considered a digital signal processing system without the processor. The DRFM is essentially an A/D converter, a memory, and a D/A converter.

1 Hardwired approaches could include both analog and digital approaches, while computed approaches are inherently digital.

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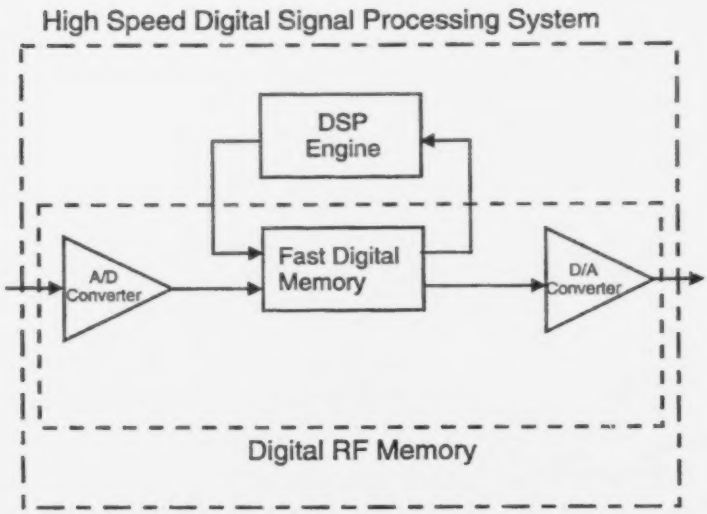

Figure 3: A Fully Computed DDDD Class Jammer

The DSP engine is able to time-shift, modulate and combine an arbitrary number of targets with independent range and Doppler, limited only by the computation power and time available. If the pulse is short, the PRI long, and the DSP engine powerful, there may be sufficient time to produce many targets. For longer pulses, fewer might be used. The use of a programmable DSP engine allows much more flexibility and allows tailoring of the technique to each particular threat. The fully computed DDDD class jammer is very simple in structure, but requires powerful DSP capability, most likely involving a number of parallel units and fast communication with memory.

Besides suitability for SAR and ISAR, fully computed range profiling is well-matched to high range resolution radar threats, since very detailed range profiles (i.e. structured targets) are possible without resorting to analog tapped delays such as SAW devices or acoustic charge transport (ACT) devices.

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Section 4.2.4 discusses DSP technology issues for HRECM. In general it may be said that fully computed HRECM is within reach of current technology for simple cases, and will become increasingly attractive as DSP technology advances over the next 5 to 10 years.

3.4 An Example Compromise HRECM Jammer

This section presents an example architecture for HRECM which implements a subset of the general architecture of Figure 1, and includes provision for digital write and read of the DRFM memory by a DSP engine. The compromise architecture is shown in Figure 4, and represents a hybrid DDDA and DDDD class HRECM jammer. For applications which require nearly instantaneous response, the hardware paths can be used to generate a limited number of simultaneous closely spaced targets, with *partial* independence of Doppler, i.e. *groups* of targets can have Doppler modulation different from other groups of targets.

In the example compromise jammer architecture, sixteen distinct range targets can be accommodated. Each group of four targets can have an independent Doppler profile imposed of arbitrary form with an arbitrary number of Doppler components (see section 4.1.1 for a discussion of Doppler modulation technology).

For relatively short pulse radars and/or long PRI radars (e.g. airborne strip mapping radar of medium resolution, high range resolution radar) the DSP engine can implement a fully computed approach to produce finely detailed range profiles (i.e. structured targets in range). Depending upon the power of the DSP engine, one might also include detailed and independent Doppler profiles for ISAR or SAR applications.

This proposed architecture is necessarily an illustration rather than a product of a tradeoff of cost versus performance, since such a trade-off is beyond the scope of the current study.

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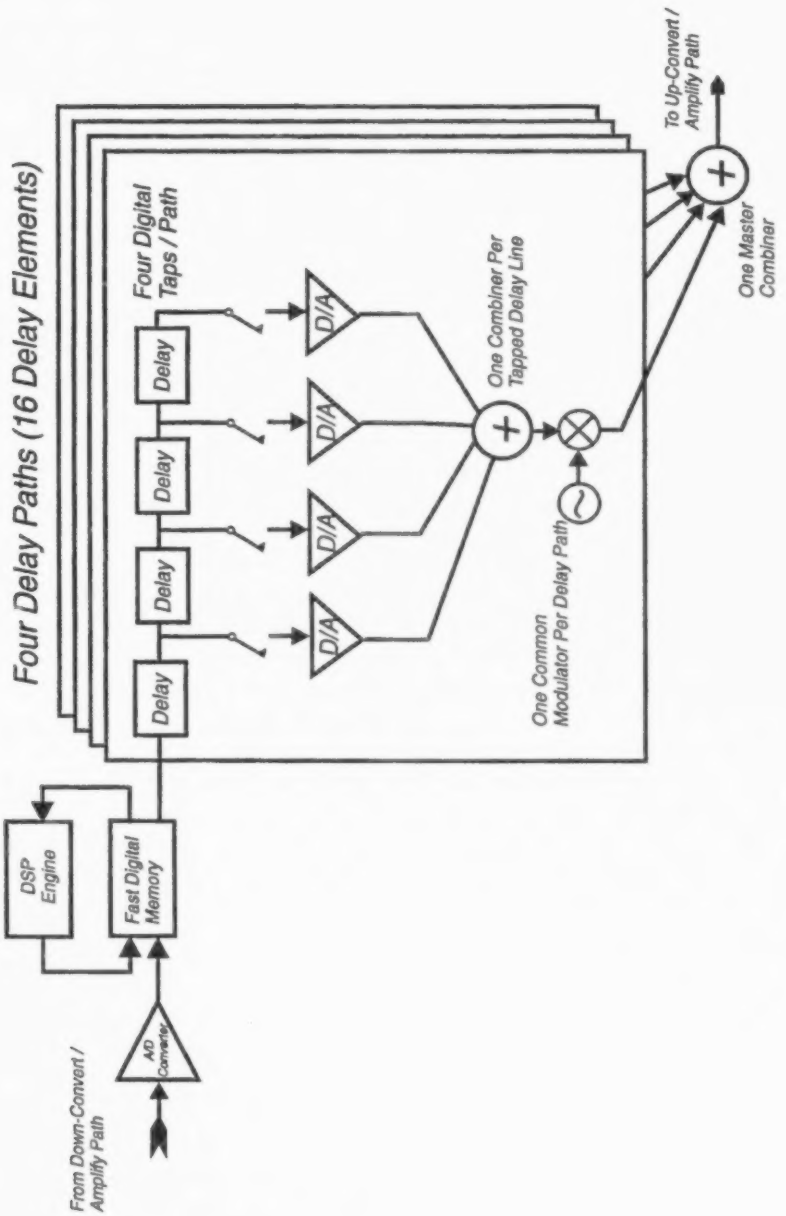

Figure 4: An Example Compromise HRECM Jammer Architecture

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4.0 Key Technology Improvements

Many aspects of current technology used in coherent jammers is well-suited to HRECM. In particular, the following mature technologies are equal to HRECM challenges:

- Digital storage of the pulse waveform
- Direct digital synthesis for Doppler modulation
- Computer control of techniques

This section describes new analog, digital, and information technology that should be improved to facilitate HRECM.

4.1 New Analog Technology for High Resolution ECM

Analog technology improvements include arbitrary Doppler modulation with low intermodulation, improved control over gain and dynamic range, and improved system linearity.

4.1.1 Arbitrary Doppler Modulation with Low Intermodulation

Current techniques for Doppler modulation introduce serious intermodulation products when multiple Doppler components are used. The intermodulations result from power variations at the LO input to the mixer. The LO is intended to operate in a switched mode, and power variations due to interference (or 'beating') of closely spaced Doppler components cause the mixer to go non-linear.

Two approaches have been identified to reduce intermodulation products during Doppler modulation:

1. Use of multiple mixers for each component followed by a power combiner
2. Use of phase shifting of the LO direct-digital synthesizer in combination with a programmable attenuator *after* the mixer

The second approach is preferable since it allows modulation by an arbitrary phasor on a pulse-to-pulse basis, and can implement arbitrary Doppler profiles.

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4.1.2 Large and Controlled Dynamic Range

Current jammer technology operates the output power amplifier in saturation, and also must provide a compressed dynamic range at the input to the analog-to-digital converter of the DRFM. These two factors lead to a constant-power jammer rather than a constant-gain jammer.

Constant end-to-end gain over a wide dynamic range with good signal-to-noise ratio is desirable for HRECM because it allows false targets to be generated which have a controlled apparent RCS regardless of radar range, antenna gain, waveform, or power. Such a system also has the potential to simultaneously counter a wide range of threats without adjustment of power levels.

There are two basic strategies to achieve constant end-to-end gain in a DRFM-based jammer:

1. Measure the incoming signal power, and adjust gain at the output stages to achieve the desired gain. (For DRFMs with limited dynamic range).

2. Use a DRFM with a large number of digital bits which can inherently support a wide dynamic range.

Use of a digitally programmable analog attenuator is probably a good way to adjust output gain for strategy one. The attenuator will come essentially for free if the modulation technique described in 4.1.1 is adopted.

Option two dictates the use of different A/D and D/A technologies which achieve higher dynamic range at the expense of sampling rates. Nevertheless, this type of technology is advancing very rapidly under the influence of civilian market forces, and will become practical for increasingly large bandwidths.

Another aspect of end-to-end gain is the need to realize output power at low noise over a large dynamic range. This requirement will likely dictate that more than one power amplifier is needed. A low noise solid state amplifier can be used for applications where low power is needed (e.g. deceptive target at relatively close range). A travelling wave tube amplifier (TWTA) can be switched in when high power is called for (e.g. larger targets at shorter ranges or obscuration techniques).[2]

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[2] Simply reducing the input signal or gain of the TWTA to achieve low power output is generally not satisfactory because the signal-to-amplifier noise ratio degrades severely.

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4.1.3 Improved Linearity

High resolution ECM requires improved linearity to avoid intermodulation products which can handicap deceptive techniques. Current ECM practices which value power output at the expense of linearity are not suitable for HRECM applications.

Overdriving of mixers, amplifiers, and power amplifiers can all produce intermodulation products. There is no need to exploit new devices, but rather a need to make linearity a design criteria over the entire signal chain.

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4.2 New Digital Technology for High Resolution ECM

Significant improvements are needed in digital technology to realize high resolution ECM. These include fully addressable DRFM memory, variable sampling bandwidth, programmable delay elements, digital signal processing, and modeling of range and Doppler compensations.

4.2.1 Fully Addressable Digital RF Memory

Current DRFM technology is able to support very high sampling rates needed for HRECM, but current designs do not emphasize random addressability of the memory, precise control over sample control, and digital input/output.

Random addressability would allow playback of portions of the captured pulse, or playback of computed ECM signals.

Current designs may not support precise delay control. The fast sampling of the DRFM makes it possible to control delay to within one inter-sample interval, but the control circuitry must permit sufficient precision in the delay representation to support this.

Finally, although the pulse waveform is converted to digital form, current designs may not permit access to the digital data itself. Digital output is desirable for test purposes and also makes some ESM applications possible. Addition of digital input (i.e. writing) to the memory makes computed ECM possible.

All of these innovations are relatively inexpensive to engineer if they are considered from the outset, but very expensive to add after-the-fact. Future laboratory jammers should include these features as absolute requirements if HRECM is of interest.

4.2.2 Variable Bandwidth DRFM Sampling

Current DRFM technology uses fixed sampling rates to support fixed, high bandwidth applications. It is desirable to support programmable bandwidth sampling which would essentially allow variable sampling rate.[3]

[3] Different anti-aliasing filters would need to be switched in to support different sampling rates.

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The purpose of allowing variable sampling rates would be two-fold:

1. More efficient use of DRFM memory to support very long pulses

2. Reduction of data volume for computed ECM applications

The well-known in-phase and quadrature representation of signals may be useful in order to increase memory efficiency.

4.2.3 Programmable Digital Delay Elements

Digital "delay lines" which can produce programmable delays are very helpful in order to produce range targets. First-In/First-Out (FIFO) memories with modest depths on the order of tens of kilosamples would be useful for this function.

A digital delay can be thought of as simply a shift register which allows data to be delayed an integer number of sample periods. For reasonable sized delays, it is convenient to use addressable memory instead of discrete shift registers. The use of a FIFO memory allows any delay up to the capacity of the memory to be produced by clocking data into the memories for the desired number of delay cycles before enabling output of data synchronous with each input clock.

The FIFO memory, like DRFM memory, would pack many sample values side-by-side to form memory words. This allows relatively slow memory to keep up with the high digitization rates of the DRFM analog-to-digital converter (A/D converter). This implies fast demultiplexing at the input to the memory (for 'packing' short sample values into longer words) and fast multiplexing at the output of the memory (for 'unpacking' into a sample stream again). To control sample delay upon regeneration, the control circuitry must be able to index individual samples within the words.

4.2.4 Digital Signal Processing

Where a computed approach is to be taken, false range targets can be produced by convolving the replica with a range profile. For a small number of range targets this consists of shifting and adding pulse replicas taken from the DRFM memory. For a detailed range profile this can be more efficiently done using fast convolution using the FFT algorithm. If time permits, target amplitude scaling and Doppler modulation could be done mathematically for each delayed replica prior to addition, making complete range and Doppler independence possible.

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DSP hardware is rapidly developing, and there exist very high throughput sub-systems with 4-16 state-of-the-art DSP processors on a single circuit board. The Sharc Pool daughter card from SKY Computer, for example, can provide between 1.44 and 5 Gigaflops (billion floating point operations per second) depending upon the configuration. Such high speed DSP systems are practical to consider for HRECM applications, and will likely continue to improve in terms of performance/cost ratio.

Shifting and adding of signals which are typically a few hundreds of points in length is not a difficult task for a processor capable of Gigaflop performance, which means that moderate numbers of delay taps will be relatively inexpensive using the fully-computed approach.

Where very fast computing power is available, fast convolution using the Fast Fourier Transform (FFT) can be used to implement finely structured targets in range with many hundreds of taps using the algorithm shown schematically in Figure 5. The incoming pulse is transformed by FFT into the frequency domain, multiplied by the discrete Fourier spectrum of a range profile, and then transformed back into the time domain using the inverse FFT (IFFT). The result for an N sample FFT and an M-sample waveform is up to N-M delay taps with arbitrary amplitude and phase profiles. This can produce the effect of hundreds of delay taps with hundreds of independent arbitrary Doppler modulators, and could not be practically implemented in a hardwired approach at any speed.

Fully computed range profiling (i.e. structured targets) with FFT fast convolution can be considered if there is sufficient time to do the forward FFT, complex multiplication, and inverse FFT within a time less than the radar PRI. If the length of the pulse and profile measured in sample points is, for example, less than 1024, then the key factor of interest is the ratio of the PRI to the 1K FFT time. This ratio must be somewhat larger than 2 for the approach to be practical. With 1K FFT times in the order of several tens of microseconds today with high end DSP systems, this approach definitely has merit, and will become more and more practical as DSP technology improves and costs come down.

Independent Doppler modulation for an arbitrary number of false targets can be contemplated by using a pre-computed two-dimensional array of complex values which can be sent one row per PRI through the algorithm shown in Figure 5. Full range and Doppler profiles for small patches can be economically stored in a few megabytes of data. This would make false targets of arbitrary form possible for SAR, ISAR and range Doppler profiling radars. The amount of computing power available, the length of the PRI, and the pulse length and bandwidth would determine whether this approach can be used in any given case.

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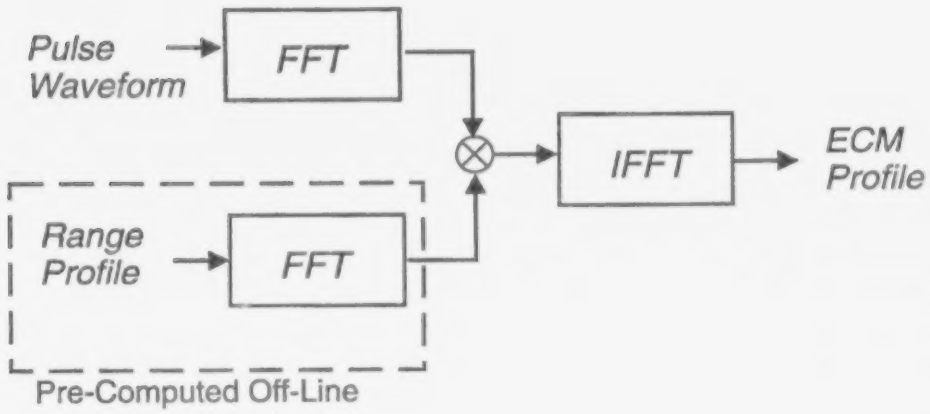

Figure 5: Simplified Diagram of Fast Convolution for Range Profiling

4.2.4 Modelling Technology

High resolution radars such as SAR or ISAR perform compensation for platform motion parallax. When a target is projected in range, the motion parallax imposed by the jammer phase may be inappropriate and cause deceptive ECM to fail to focus in the threat radar data processor.

Algorithms for efficiently computing range and Doppler modulations for computed ECM are also needed if full SAR or ISAR image injection is to be achieved using a fully-computed approach.

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5.0 Conclusions

High resolution ECM (HRECM) requires precise control over range delay and Doppler modulation, which must be supported by sufficiently precise control. Doppler modulation of an arbitrary nature can be achieved by upgrading modulation techniques to avoid intermodulation and creating the narrowband arbitrary Doppler waveforms using digital computation. Producing closely-spaced range targets with superimposed pulse reconstructions is much more difficult to achieve and requires either separate programmable tapped delays or fast digital computation.

Improvements in linearity and constant-gain operation are important if realistic false targets are to be reliably produced. These require a change in engineering approach rather than utilization of new devices.

Production of superimposed fully independent range and Doppler profiles is needed to produce arbitrary false image or range profile patches. The hundreds or thousands of false range-Doppler targets of varying intensity requires either a large number of independent delay paths with independent modulators, a fast digital signal processing engine, or both.

The DRFM design approach for HRECM should stress precise control over range delay, addressable DRFM memory, variable sampling rates, digital I/O, and tight integration with a digital signal processing engine.

Digital signal processing technology offers excellent prospects for allowing fully computed complex ECM techniques in the future, and can support simple ECM techniques now. Despite this fact, hardwired delay paths with dedicated Doppler modulators will probably always be needed where instantaneous response is needed.

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References

Digital Signal Processing, A.V. Oppenheim and R.W. Schafer, Prentice-Hall Inc., © 1975.

GC2011 Digital Filter Chip Datasheet, GRAYCHIP, INC., Palo Alto, California, 26 January 1998.

High-Resolution Radar, Second Edition, D.R. Wehner, Artech House, © 1995.

Investigation of ECM Techniques for Countering Spaceborne Synthetic Aperture Radar, Vantage Point International Inc., 13 April 1993.

MiroTech Training Seminar Notes, MiroTech Microsystems Inc., 19 January 1998.

TMS320 Digital Signal Processing Solutions Reference Guide, Texas Instruments Incorporated, 1996.

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